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The Economics of Forest Carbon Offsets

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Abstract

Annually, nearly 500 gigatonnes of CO_2 are exchanged between terrestrial ecosystems and the atmosphere, and this exchange is clearly affected by human activities related to the Earth's forests. Governments are therefore willing to draft legislation incentivizing forest activities that sequester carbon to combat climate change. In this review, we examine issues related to the creation of carbon offset credits through forest conservation, burning of wood biomass in lieu of fossil fuels, and intensive commercial management that accounts for all carbon fluxes, including postharvest. In doing so, we study the costs of monitoring, measuring, and contracting; the principal-agent problem; and questions related to life cycle analyses of CO_2. We can only conclude that greater care is likely needed in the future to identify carbon offsets from forestry activities if these are to be traded in emissions markets.

1. INTRODUCTION

The globe's forest ecosystems constitute an important natural resource that provides commercial benefits, ecological services, and recreational and nonuse values. They also play an important role in the Earth's climate system, particularly as a source of carbon dioxide (CO_2) emissions and as a carbon sink. Some 2,200 gigatonnes (Gt) of carbon are contained in terrestrial vegetation and soils, with 1,200 Gt stored in the globe's forests: 323 Gt of carbon are stored in the boreal forests of Russia, 223 Gt in Canada's boreal forests, and 229 Gt, 115 Gt, and 90 Gt in the tropical forests of the Americas, Africa, and Asia, respectively. Annually, 125 Gt of carbon, or nearly 460 Gt CO_2, are exchanged between terrestrial ecosystems and the atmosphere, representing two-fifths of the total exchange between the earth and the atmosphere, with forest ecosystems accounting for 80% (FAO 2014). Clearly, forests play an important role in determining the concentration of CO_2 in the atmosphere, with forest management and human activities related to afforestation, reforestation, and deforestation (ARD), as well as postharvest use of wood biomass, affecting the globe's CO_2 balance.

Because forests play a significant role in the Earth's carbon balance, governments are willing to employ policies that affect forest carbon fluxes as a strategy to combat climate change.[1] This was the case for the 1997 Kyoto Protocol of the United Nations' Framework Convention on Climate Change (UNFCCC). To prevent the costs of compliance from rising inexorably, countries opted for a variety of instruments they could use to meet their self-imposed targets, including forestry activities. With this in mind, this review's focus is on forest economics and policy as they relate to the role of the forest sector in mitigating climate change.

Because forests are capable of removing CO_2 from the atmosphere and storing it as carbon in living and dead biomass and product sinks, forest activities can contribute to climate change mitigation. If the costs of harvesting mature trees exceed the commercial benefits, the forest will be left as wilderness, but logging should also be prevented if more CO_2 is released than is socially desirable, or if unsustainable forest operations degrade the forest to such an extent that more CO_2 is released than is socially optimal. This implies that subsequent regeneration may be unable to recover the CO_2 released; that is, the contribution to global warming caused by deforestation or degradation is less than the benefits from harvesting the trees plus the mitigation benefits of planting a new forest. As discussed in Section 5, if carbon can subsequently be stored in products or if wood biomass can substitute for the burning of fossil fuels, thereby lowering the overall release of CO_2, it may yet be beneficial to harvest trees rather than preserve the forest.

To better understand the economic challenges of forest-sector carbon offsets, we discuss (*a*) forest conservation, (*b*) burning of wood biomass in lieu of fossil fuels, and (*c*) intensive commercial management that accounts for all carbon fluxes. These topics are covered in Sections 3, 4 and 5, respectively. We begin, however, by examining the importance of carbon offsets and the challenges in relying on them to mitigate climate change. The overall discussion builds on an earlier review by Sedjo & Sohngen (2012).

2. FOREST CARBON OFFSETS

Greenhouse gas (GHG) emissions trading is the main policy vehicle considered for mitigating climate change, although regulations, subsidies for nonfossil fuel energy, and carbon taxes are employed in various jurisdictions (Beck & Wigle 2014). Emissions trading occurs when there is an official cap on GHG emissions, and emitters that exceed their individual targets can purchase

[1]The carbon flux refers to the net carbon released to or removed from the atmosphere over a period of time.

emission reduction permits in the compliance (mandatory) market from those who are below their emissions target. A carbon offset then refers to an emission reduction or equivalent removal of CO_2 from the atmosphere that is realized outside of the compliance market but can be used to counterbalance GHG emissions from the capped entity.

Forest-sector carbon offsets can reduce emitters' costs of complying with emission reduction targets, while buying time to enable them to develop and adopt emission-reducing technologies. On the negative side, offsets reduce incentives to invest in emission-reducing technologies because they lower the cost of emitting CO_2. Further, carbon offsets are fraught with problems related to uncertainty and corruption (Helm 2010, van Kooten & de Vries 2013).

Tree planting and activities that enhance tree growth clearly remove carbon from the atmosphere and store it in living and dead biomass; thus, afforestation and reforestation should be eligible activities for creating carbon offsets (IPCC 2000, 2006). Afforestation is defined as the establishment of trees on land that has not in the recent past been forested and where trees would not otherwise be planted. In a similar fashion, reforestation refers to tree planting on a site previously forested, but where it is unlikely that the forest will regenerate on its own. Likewise, silvicultural activities (e.g., fertilization) that enhance tree growth or otherwise increase the amount of carbon sequestered in a forest ecosystem would be eligible. Further, because deforestation releases significant amounts of CO_2 into the atmosphere, the preservation and conservation of forests—that is, preventing degradation, converting to other uses, or simply delaying harvest—have been proposed as eligible but controversial means to obtain carbon offset credits (see Section 3).

Given that Kyoto's time frame did not permit countries to adjust their timber portfolio to take advantage of incentives to create carbon offsets, the 2001 Marrakech Accord permitted countries to offset up to 9.0 megatonnes (Mt) of carbon (or 33 Mt CO_2) during each year of Kyoto's first compliance period (2008–2012) through verified forest management activities that enhance carbon uptake. These could be claimed only against ARD debits, however. In addition, some countries, most notably Canada (44 Mt CO_2/year), the Russian Federation (121 Mt/year), and Japan (48 Mt/year), could claim carbon credits from business-as-usual forest management that need not be offset against ARD debits. It is well known that allowing afforestation–reforestation activities in lieu of CO_2 emissions reduction poses a number of challenges (Sedjo & Sohngen 2012, van Kooten et al. 2014), which are discussed in the remainder of this section.

2.1. Additionality and Leakages

The only activities that count toward the creation of carbon offsets are those that are additional, reducing atmospheric CO_2 beyond what would occur in the absence of incentives. If the tree planting activity would have been undertaken in the absence of policy to mitigate climate change, the carbon benefits (i.e., offset credits) related to the project should not be counted. In practice, there are many instances in which trees are planted for a variety of reasons unrelated to climate change, but those incurring the planting costs promote their project as one that creates carbon offsets. These offsets are then put up for sale, usually in the voluntary market, but if properly certified by the sponsoring government, can be traded in the mandatory market.[2] Similarly, proponents of forest conservation might lobby for carbon offset credits even though forest conservation might take place in any event for reasons unrelated to climate change mitigation. Concerns related to

[2]Offset credits can be sold in a voluntary market where buyers use carbon offsets to demonstrate that their activities are somehow carbon neutral. Although such credits may be certified, they cannot be used by economic agents (or countries) to meet emission-reduction targets. Meeting targets requires the purchase of offsets in a mandatory/compliance market.

the information asymmetries and lack of appropriate methods for evaluating additionality are well documented (He et al. 2014, Purdon 2015, Wara 2008).

Along similar lines, payments that promote direct changes in land use for the purpose of carbon sequestration lead to changes in land use elsewhere that release CO_2, something known as a leakage. At the microlevel, a landowner who is paid to plant trees might compensate for the loss in agricultural output by removing trees and planting crops elsewhere on her farm. At a macrolevel, tree planting causes agricultural output to decline, raising prices and leading landowners to expand cultivation onto marginal lands currently in permanent pasture or forest, thereby releasing CO_2. Even forest conservation might lead to greater harvests elsewhere, which occurred when the United States protected forests in the Pacific Northwest to protect the endangered northern spotted owl. Leakages of 43% to 85% have been documented, and a failure to account for leakages can underestimate the costs of CO_2 uptake by one-third (Arroyo-Currás et al. 2015, Boyland 2006, Paroussos et al. 2015).

2.2. A Plethora of Instruments

The Kyoto Protocol employs a variety of instruments that developed countries can use to achieve their targets. These countries can (*a*) reduce domestic CO_2 emissions, (*b*) purchase allowances from other rich countries (whose emissions are below target), (*c*) sequester carbon in domestic biological sinks, (*d*) purchase certified emission reductions (CERs) via the Protocol's Clean Development Mechanism (CDM), and (*e*) create earned reduction units (ERUs, which equal CERs) by investing in emissions reduction projects in economies in transition through Kyoto's Joint Implementation mechanism. Forestry projects that sequester carbon are also eligible for CERs and ERUs. The main problem with all these instruments is their lack of commensurability (van Kooten 2009a), although future climate agreements appear to retain a variety of instruments to provide countries with sufficient flexibility and opacity to meet emission reduction targets.[3]

The problem is heightened when markets for other environmental services also exist. The selling of multiple environmental services, such as carbon offsets and contracts to protect threatened wildlife habitat, in more than one market is known as double-dipping (Woodward 2011). It also occurs, for example, when a developed country invests in a tree planting project in China, and both countries claim the carbon reduction benefits—the developed country claims a CER, and the developing country claims a domestic reduction.

2.3. Transaction Costs and Governance

Transaction costs refer to measuring, monitoring, verifying, enforcing, and negotiating trades, whereas governance refers to the means by which trades are made. Both are affected by the institutional framework within a country and the nature of agreements among independent jurisdictions (see van Kooten 2004, 2009b). This would include such things as social capital (trust), rule of law, and the freedom to engage in contracts that include credible threats in the event of noncompliance.

Measurement and monitoring are particularly pertinent for forestry in places where the tracking of carbon fluxes is extremely challenging. Contracts to create carbon offsets on forestlands are costly to negotiate and difficult to enforce because of asymmetric information

[3]The 2015 Paris Agreement leaves it up to individual countries to determine how they will achieve their "intended national determined contributions," requesting only that countries must do better than the targets (United Nations 2015, p. 3).

and the principal-agent (PA) problem (Bogle 2012; Bogle & van Kooten 2013, 2015). Of course, measurement and monitoring will depend on the effectiveness of rule of law, which is weak in most developing countries (De Soto 2000).

With forest carbon offset contracts, several PA layers make it difficult to identify contracting parties. The top-end principal is the ultimate buyer of the offset credits who sets them against CO_2 emissions, whereas the bottom-end agent is the landowner. Various PA relations to certify offsets and facilitate transactions exist between the eventual buyer and landowner, as the vertical chain could include tenants, aggregators of offsets, and certifiers. Asymmetric information is exacerbated by these PA layers, creating further challenges in determining the validity of carbon offsets (Mason & Plantinga 2013).

To militate against these PA problems, governments and/or environmental nongovernmental organizations (NGOs) certify carbon offsets for sale in mandatory or voluntary markets, although there is no guarantee that the certifiers ensure forestry projects that truly offset CO_2 emissions. As experience with the European Trading System (ETS) has shown, firms' self-declared emission levels are well above their actual emissions, thereby making it easy for them to generate offsets known as European unit allowances for sale on the ETS. This led to the collapse of the ETS in early 2013, with prices well below €3 per tonne of CO_2 (t CO_2) after achieving a maximum of €32/t CO_2 shortly after its implementation in 2005. Even under Phase III (2013–2020), trades have remained below €10/t CO_2. With corruption being an underlying concern, monitoring and enforcement impose additional costs and may explain why it took so long to certify the first CDM forestry project and why it did not deliver the agreed upon carbon uptake (Gong et al. 2010, van Kooten et al. 2009).

Economists have addressed the PA problem by focusing on the payment mechanism. To encourage on-the-ground agents or landowners to participate in tree planting projects, for example, an upfront payment is clearly required, often to cover the initial planting cost. Then a second and final payment would be made at the end of the contract period, with this final payment providing the needed incentive to keep agents from violating the contract. To protect forestland from being converted to an alternative use, Engel et al. (2012) argue that a fixed per hectare payment plus annual payments that vary according to an index of agricultural prices are more efficient than a system in which variable payments are tied to the price of carbon. The difficulty here is that the principal does not have sufficient information about the relations between the intermediary and on-the-ground agents, the alternative land uses available, and how the opportunity costs of land might change during the contract period. With this in mind, others have attempted to entice the landowner to reveal his or her marginal cost of converting land (Arguedas & van Soest 2011).

3. REDUCED EMISSIONS FROM FOREST CONSERVATION: REDD AND REDD+

Forest protection mitigates climate change by preventing CO_2 from entering the atmosphere as a result of forest exploitation, especially tropical deforestation that accounts for perhaps as much as 20% of total emissions of anthropogenic GHGs. Forest conservation activities were not eligible for carbon offsets under Kyoto, but concerns about tropical deforestation have resulted in efforts to make activities that Reduce Emissions from Deforestation and forest Degradation (REDD) eligible for certified offset credits. As a result of negotiations at Cancun in December 2010, the narrow role of REDD was expanded to include sustainable management of forests, forest conservation, and the enhancement of forest carbon stocks, collectively known as REDD+ (Bosetti & Rose 2011, Buttoud 2012, Kaimowitz 2008, Law et al. 2012, Sedjo & Sohngen 2012). In this way, it was possible to link the UNFCCC and the UN's Convention on Biological Diversity,

the other agreement signed at the 1992 Earth Summit in Rio de Janeiro. With the 2015 Paris Agreement, signatories are thus encouraged to implement "...positive incentives for activities relating to reducing emissions from deforestation and forest degradation" (United Nations 2015, p. 23).

Some argue that the benefits of REDD and REDD+ activities for climate change can be significant. Sathaye et al. (2011) indicate that the noncarbon environmental benefits of forest preservation amount to 57.5–76.5% of the total protection benefits. Bosetti et al. (2011) report that a greater reliance on reduced deforestation and other land-use activities could reduce the net costs of achieving a global target of 550 parts CO_2 per million (ppm) in the atmosphere by upward of US$2 trillion, an estimate cited by many climate researchers. It originates with Tavoni et al. (2007), who conclude that by linking forest management to the carbon market, there is a potential free saving of 50 ppm in 2100, which corresponds to a decrease in the projected global average temperature in 2100 by 0.25°C. The saving results from a significant increase in the supply of carbon offsets and thus a decrease in the price of carbon, although Tavoni et al. (2007) do not attribute this saving entirely to forest conservation (as they include other forest activities). Further, the savings are much lower if one considers the opportunity cost associated with delayed or avoided harvests (Man et al. 2015). Kindermann et al. (2008) estimate that by reducing global deforestation by 50%, CO_2 emissions could be reduced by 1.5–2.7 Gt per year at an annual cost of $17.2–28.0 billion. However, "these estimates are based on economic models that do not consider transactions costs and other institutional barriers, which raise costs in practice" (Kindermann et al. 2008, p. 10306). Overall, these estimates are derived from a variety of models used by the Intergovernmental Panel on Climate Change (IPCC) in its projections (van Kooten 2013, pp. 102–110, 125–134) and based on the assumption that a new climate agreement will be made and administered under an ideal global governance structure.

The complexity introduced by REDD+ impacts the carbon price mechanism; by supplying the market with REDD+ carbon offsets, the price mechanism ensuring that the demand for credits equals supply is distorted because sales of REDD+ credits are used in place of emissions reductions. REDD+ offsets lower the need for emission reductions to meet targets in compliance markets. Indeed, this is their purpose, although they are also a mechanism for developed countries to pay for environmental services provided by developing countries. Although the concept is a reasonable one, implementing payments for environmental services on an international scale is proving much more difficult than anticipated (Angelsen 2014). Besides additionality, leakage, and double-dipping, it is difficult to establish a business-as-usual baseline against which REDD+ credits are to be determined (Mbatu 2015). As a result, transaction costs and governance—contracting, measuring, and monitoring compliance—are major concerns related to the use of carbon offset credits from forest conservation (see Aud. Gen. BC 2013, Malmsheimer et al. 2011, van Kooten et al. 2015).

4. CARBON FLUX AND BIOMASS ENERGY

The role of forests in mitigating CO_2 now extends beyond the forest as governments increasingly turn to wood biomass for energy (McDermott et al. 2015). Although biomass includes agricultural crops and municipal waste, it usually refers to wood biomass in the form of wood pellets that are relatively easy to produce and transport. More utilities are investing in power plants fueled by wood pellets, or they are retrofitting coal plants to cofire with pellets to reduce their CO_2-emissions intensity (Hayter et al. 2004). Retrofitting coal plants is appealing due to the low incremental investment required and because energy produced from biomass is considered to be carbon neutral; CO_2 emitted during production of electricity is subsequently removed from the atmosphere by

newly planted trees (e.g., Hayter et al. 2004, p. 8; IPCC 2006, 2014; Skone et al. 2012, p. vii). Johnston & van Kooten (2015b) comprehensively describe the economics behind cofiring.

4.1. Tracking Carbon Fluxes: The Carbon Life Cycle Analysis

There exists a rich body of research on the impact of GHG emissions on substituting forest bioenergy for fossil fuels (see Miner et al. 2014; Sedjo 2011, 2013). Physical scientists have conducted much of the research and emphasized the carbon life cycle characteristics of biomass energy (Cherubini et al. 2011, Helin et al. 2013, McKechnie et al. 2011). In the various analyses, it is assumed that carbon dioxide entering the atmosphere as a result of fossil fuel burning remains in the atmosphere indefinitely, so that any such emissions are considered irreversible. In contrast, it is assumed that emissions of CO_2 from biomass burning can be removed from the atmosphere by the Earth's carbon sinks. These distinctions are important.

Walker et al. (2013) determine that if the source of biomass is dedicated harvests of mixed wood, it takes from 45 to more than 90 years for the carbon debt to be recovered in the case of gas electric plants and coal plants, respectively. However, if the only source of biomass energy is logging residues, it takes only 10 to 30 years to recover the carbon debt. The reason for this difference is the life cycle analysis (LCA): The carbon associated with the harvesting of whole trees for burning would otherwise have remained on-site sequestering carbon. In the case of logging residues, the trees would have been cut regardless, and the carbon associated with the residues would otherwise have been released to the atmosphere through decay if it was not used as bioenergy. Some scholars have criticized this argument, however, as it places undue restrictions on the analysis; when relaxed, the argument paints a different picture (Sedjo 2013). Several studies have subsequently proposed alternative LCAs for carbon fluxes associated with biomass burning.

McKechnie et al. (2011) build on Walker et al.'s (2010, 2013) analyses by focusing to a greater extent on the forest ecosystem carbon dynamics. In their LCA, they consider the changes in forest carbon resulting from harvest for bioenergy plus the changes in GHG emissions when biomass is converted to wood pellets and cofired with coal to produce electricity. However, their conclusion is similar to that of Walker and colleagues: The benefits of generating electricity from biomass depend on whether standing timber or logging (forest floor) residuals are used for bioenergy. The authors find that if pellets are produced from standing trees, the time taken to eliminate the carbon debt from biomass burning takes some 38 years. If pellets are produced from forest residuals, the break-even point occurs after 16 years. If 15% of the biomass is not needed to dry the wood (as originally assumed), the times required to obtain climate mitigation benefits are reduced to 29 years and 11 years, respectively. The authors also find that conversion of biomass to ethanol is a poor alternative, sometimes taking more than 100 years to eliminate the initial carbon debt. Finally, McKechnie et al. (2011, p. 794) acknowledge that there would be no carbon debt but only a carbon dividend if standing trees are harvested and converted to products that replace steel and cement in construction (see below).

Cherubini et al. (2011) use the notion of global warming potential (GWP) to determine the prospective carbon dividend from biomass burning. The GWP of CO_2 from fossil fuel burning is taken to equal one regardless of the time horizon. Thus, a distinction is made between CO_2 molecules released by burning fossil fuels and those released when burning biomass; CO_2 emitted from biomass is denoted bioCO_2 to distinguish it from CO_2 emitted by fossil fuels. Because CO_2 from fossil fuel burning cannot be removed from the atmosphere by assumption, the GWP_{bio} is a measure of the relative benefit of burning biomass.

Cherubini et al. (2011) find that if the forest rotation age is 40 years and the time horizon is 100 years, the approaches of Walker et al. (2010) and McKechnie et al. (2011) would result

in a GWP_{bio} of 0.43, compared to 0.16 if the entire terrestrial vegetation plus ocean sinks were considered rather than only the vegetation sink from which the biomass originated. For a forest with a rotation age of 80 years, the comparable GWP_{bio} values are 0.86 and 0.34, respectively. For clarification, had the GWP_{bio} values been greater than 1.0, this would have meant that for equivalent emissions of CO_2 per unit of electricity produced, fossil fuels would be the preferred method of generating electricity. It turns out that GWP_{bio} values exceed 1.0 only when the time horizon is particularly short relative to the rotation age. Bioenergy is preferred to fossil fuels when GWP_{bio} is less than 1.0, which is almost always the case in Cherubini et al.'s (2011) LCA.

Kurz et al. (2013), Lemprière et al. (2013), and Smyth et al. (2014) take a dynamic forest ecosystem approach that distinguishes carbon fluxes associated with human activities (planting, fertilizing, thinning, harvesting) from those associated with natural forces (weather, wildfire, pests, disease). This approach considers carbon stored in the ecosystem and postharvest wood product pools, the CO_2 benefits of replacing fossil fuels with biomass as an energy source, and the CO_2 emissions avoided from making cement and steel when wood replaces these products in construction.[4] In their life cycle analysis of carbon in boreal ecosystems, for example, Kurz et al. (2013, p. 263) note that "The age-class structure currently found in North America's boreal forests is a transient, nonsustainable phenomenon arising from a period with higher disturbance rates followed by a period with lower disturbance rates," with carbon stocks currently greater than their long-term sustainable maximum. If left undisturbed, these forests will inevitably become net emitters of CO_2 to the atmosphere. However, the boreal forest becomes a net carbon sink once forest management, solid wood product sinks, and opportunities for bioenergy are considered within the LCA framework (Lemprière et al. 2013, Smyth et al. 2014). This is discussed further in Section 5.

4.2. Challenges to Bioenergy

When biomass is burned in place of fossil fuels, the incremental CO_2 can remain in the atmosphere for several decades, in which case it contributes to climate forcing. Thus, if there is some urgency to remove CO_2 from the atmosphere to avoid the associated climate forcing, the timing of emissions and removals of carbon are important, with current emissions of CO_2 and removals from the atmosphere by sinks more important than later ones.[5] This implies that carbon fluxes need to be weighted as to when they occur, with future fluxes discounted relative to current ones, which, as noted above, is the purpose of the GWP measure (Galik & Abt 2012; Helin et al. 2013, p. 481; Lemprière et al. 2013, p. 308; Schlamadinger & Marland 1999; van Kooten 2009a).[6] Indeed, economists since Ciriacy-Wantrup (1968) have used weights to compare the physical rates of resource extraction (e.g., the rate that oil is pumped from a well) to determine whether a policy is conserving or depleting. With this in mind, Johnston & van Kooten (2015a) show that the urgency to deal with climate change erodes the assumption that bioenergy is carbon neutral.

Additional concerns have been cited. First, Sedjo & Tian (2012) and Sedjo (2013) argue that if decision making is characterized by rational expectations (Muth 1961), landowners will plant trees in anticipation of their use as a bioenergy source. Thus, any carbon released by burning biomass

[4]Concrete requires 5 times and steel 24 times more energy to produce than an equivalent amount of sawn softwood. Wood is also 5 times more insulating than concrete and 350 times more insulating than steel.

[5]"The lower the desired limit of global temperature increase, the lower the stabilization level of greenhouse gas concentrations in the atmosphere, and the more rapidly the greenhouse gas emissions need to be reduced" (Helin et al. 2013, p. 476).

[6]Discounting of physical carbon is not to be confused with dual discounting of consumption and environmental quality, in which both are measured in monetary terms (see Weikard & Zhu 2005).

to generate electricity today would have been sequestered beforehand, leaving no carbon debt to consider.

Second, the largest impacts of wood bioenergy likely relate to land-use changes and the effects on wood products. Because land is the most important input into the production of bioenergy, incentives to produce bioenergy distort land use by converting cropland from food production into energy crops, including wood biomass (Ince et al. 2011, 2012; Moiseyev et al. 2011), thereby raising food prices.[7] It may even be the case that CO_2 emissions are increased rather than reduced as a result of distorting land use, especially when the increased chemicals used in their production are taken into account (Crutzen et al. 2008; Klein & LeRoy 2007; Searchinger et al. 2008, 2009).

Third, policies that incentivize production of wood pellets for generating electricity have international consequences. Raunikar et al. (2010) and Buongiorno et al. (2011) examine trade in fuelwood, which constitutes roundwood used primarily for cooking and heating. They conclude that increased fuelwood demand leads to the convergence of fuelwood and industrial roundwood prices, while the prices of other forest products, including sawnwood and panels, rise significantly. Johnston & van Kooten (2016) find that doubling the demand for wood pellets in the European Union (8.3 Mt were burned in 2012) would increase the cost of pellets for electricity generators by nearly 90%. Bioenergy subsidies increase demand for residual fiber, resulting in competition between wood pellet producers and producers of traditional wood products; often the traditional producers win out, but if subsidies are high enough, more fiber is directed to wood pellet production and less carbon enters the wood product sinks (Niquidet & Friesen 2014, Stennes et al. 2010).

Finally, subsidies that increase the demand for wood residues for bioenergy have two offsetting impacts: They (*a*) increase the production of lumber and plywood and (*b*) reduce the production of pulp, oriented strand board, and medium density fiberboard, among others. An increase in the value of sawmilling residues effectively increases the value of a log to the sawmill operator or, analogously, reduces the cost of producing lumber (Latta et al. 2013). This causes the sawmilling sector to increase demand for logs and thereby increase lumber output and associated sawmill residues (Abt et al. 2012, Johnston & van Kooten 2014).

4.3. Forest Certification

There is increasing pressure for governments to ensure that wood pellets are sourced from certified forests so they can avoid or at least deflect claims that the use of wood pellets might lead to an increase in CO_2 emissions for reasons related to unsustainable forest management practices. The Forest Stewardship Council (FSC) and the Program for the Endorsement of Forest Certification (PEFC) are the only global organizations that certify sustainable forest management practices and the chain of custody from the forest to the end-user. The FSC has its own criteria and certification process, whereas the PEFC is an umbrella organization that assesses and recognizes the criteria and processes of national certifiers. Additionally, seven European bioenergy producers have formed the Sustainable Biomass Partnership to establish certification criteria for wood pellet producers and users.

Certification poses a major challenge to wood pellet producers. Most forests in the United States are not certified, with the proportion of forestland certified for sustainable management much lower there than in Canada and the European Union (FAO 2015, PEFC 2015).

[7] Conversion of land is also affected by owners' risk attitudes, with less land converted to bioenergy purposes if future biomass markets are uncertain (Hallmann & Amacher 2012).

Further, criteria for certification of wood pellets by the European Union could be quite stringent (Sikkema et al. 2014), so much so that the US Industrial Pellet Association is concerned that recent EU requirements to ensure wood pellets come from certified forests or come with a chain of custody certificate could lead to a reduction in their access to the European market (Ginther 2015). This would increase the costs of wood pellets and make bioenergy a less attractive option.

5. MANAGING FOR CARBON: CARBON POOLS AND FOSSIL FUEL SUBSTITUTION

Rather than focusing solely on bioenergy and forest activities that prevent deforestation and forest degradation, we also need to examine the carbon flux associated with various forest ecosystem pools, carbon sequestered in postharvest wood product pools, and the CO_2 emissions avoided when wood replaces concrete and steel in construction. A comprehensive approach to forest management that takes appropriate account of carbon fluxes will likely provide the greatest climate mitigation benefits the forest sector can offer (Lemprière et al. 2013). For example, for Canada's boreal forests, studies find that commercial logging with timber processed into wood products is preferred to storing carbon in an unmanaged forest ecosystem (Smyth et al. 2014). Further, there is a greater carbon dividend if timber is processed into wood products as opposed to using wood biomass to produce energy (Kurz et al. 2013). With the exception of a limited amount of sawmill residues, which are utilized on-site for heat and power or by pulp mills, logging residues and roadside wastes are generally too expensive to transport out of Canadian forests (Niquidet et al. 2012, Stennes et al. 2010).

To identify the forest activities that lead to the greatest carbon uptake, a comprehensive management model and robust data are needed. Using a geographic information system model of timber inventory for various biogeoclimatic zones in British Columbia in conjunction with the TIPSY [**T**able **I**nterpolation Program for Stand Yields, which employs the Canadian Carbon Budget Model (Kurz et al. 1996)] growth, yield, and carbon calculator (**https://www.for.gov.bc.ca/hts/growth/tipsy/tipsy_description.html**), van Kooten et al. (2015) develop a forest management model that examines strategies for generating carbon offsets for sale in voluntary markets. In contrast to the conservation plan proposed by an environmental NGO, the authors find that carbon uptake was much greater if a landowner was incentivized to manage the forest sustainably for its commercial timber and carbon sequestration values. Further, measured carbon uptake is even greater if avoided emissions related to the substitution of wood products for nonwood products in construction are also counted.

The importance of postharvest wood product carbon sinks should not be underestimated. There remains significant potential for wood product sinks to expand, thereby storing carbon for extended periods (Kurz et al. 2013, van Kooten et al. 1999). For example, technological advances in engineered wood products have enabled the construction of multistory wood buildings and state-of-the-art multipurpose (even irregularly-shaped) buildings. Engineered products are now much less vulnerable to fire and pests, and wood buildings require less energy to heat or cool, thereby further reducing GHG emissions (Green & Karsh 2012).

Additional carbon savings could be counted in the creation of carbon offsets if one included emissions avoided by using wood products in construction as opposed to relying on emission-intensive products such as steel and concrete. According to Hennigar et al. (2008), savings could vary from 0.3–3.3 t CO_2/m^3. However, the inclusion of avoided emissions raises a question regarding the identification and measurement of carbon offsets. The externality cost of CO_2 should be credited as an offset for sale in a carbon market at the time uptake occurs or as a requirement to purchase offsets when CO_2 is emitted, and both at source. In that case, carbon sequestered

Table 1 Forest growth data for western Canada

Item	Coastal rainforest	Interior/boreal forest	Genetically-enhanced interior/boreal forest
Parameter values for $v(t) = \alpha(1 - e^{-\delta t})^{\gamma}$			
α	1,094.00	402.00	396.00
δ	0.0294	0.0413	0.0140
γ	6.47	3.90	3.70
Value of φ (kg/m^3)	182	203	220
Average price of timber (\$/m^3)[a]	\$94.91	\$60.87	\$60.87
Average cost of harvesting/hauling (\$/m^3)[b]	\$67.07	\$34.87	\$34.87

[a]Information on log prices (as of March 2015) from **http://www.for.gov.bc.ca/hva/logreports.htm**. These are average prices, but coastal hemlock-balsam logs can sell for \$120–150/m^3 and fir for \$140–200/m^3, whereas interior spruce-pine-fir sell for \$62–80/m^3. Values are in Canadian dollars.

[b]Data from TIPSY growth model. Costs can vary among regions due to many factors.

in growing trees and subsequently stored in wood product sinks is eligible for carbon offsets; however, emissions avoided from the production of nonwood products when wood substitutes for steel or concrete should not be counted. CO_2 emissions from the production of steel and concrete would normally be penalized. Under emissions trading, a reduction in the sector's emissions could lead to credits that could be sold in the mandatory market. Assigning the same avoided emissions to the forestry sector as carbon offsets results in double-counting.

The same would be true of the unmanaged forest, because offsets are created with respect to a hypothetical counterfactual—a political construct. It would also be true of bioenergy: CO_2 released from burning biomass to generate electricity would be treated as an emission (requiring purchase of offsets). CO_2 emissions saved from not burning fossil fuel should be credited offsets that could then be sold to the biomass thermal plant, and offsets would be generated as growing trees sequester carbon from the atmosphere.

Although still missing the mark due to many uncertainties, a complete forest management model is required to capture many of the nuances associated with the creation of carbon offsets. Management decisions are affected by the future and spot prices of carbon offsets in voluntary and mandatory markets. With the exception of physically measuring carbon fluxes each period, there appears to be no other way to determine how many carbon offsets that a forest project might be able to offer for sale on voluntary or mandatory markets. Forest models help facilitate offset trading by reducing transaction costs, although the lack of forestry projects eligible for CERs under the CDM suggests that transaction costs remain onerous. As of July 31, 2015, and since November 2007, only 71 afforestation and reforestation projects had been certified, representing only 0.8% of registered CDM projects and much less of CO_2 credits (**https://cdm.unfccc.int/Registry/index.html** and **http://www.cdmpipeline.org/**). Nonetheless, it is possible to gain insights into the potential to create carbon offsets in forestry by looking at the impact of a carbon price on rotation ages. Therefore, in the remainder of this section, we examine the impact carbon offset incentives might have on harvest decisions and thereby the potential of models to direct forest activities toward mitigation of climate change.

5.1. Financial Rotation Age

First consider the optimal financial rotation age, but ignore the value of carbon. A forest site is generally harvested on a periodic basis; it takes time for trees to grow, and when they reach

maturity, the forestland owner will harvest and sell the trees. Suppose the rate of growth of the value of a forest stand is given by $g(t) = V'(t)/V(t)$, where $V(t) = (p - c)\, v(t)$ is the value of the stand at time t, p is the price of logs ($/m^3), c is the cost of harvesting logs ($/m^3), and $v(t)$ is the volume of commercial logs (m^3) on the site at time t. If log prices and harvesting costs are constant, then $g(t) = v'(t)/v(t)$. The general rule for determining when to harvest the trees is this: If the rate r used to discount monetary values exceeds $g(t)$ at any time, the stand should be harvested immediately, whereas harvest should be delayed as long as $g(t) > r$.

The forgoing rule ignores future opportunities, however. If the landowner can replant the site after harvest and harvest trees again at a future date, it will pay to harvest trees somewhat earlier than indicated by the above rule because this enables the landowner to harvest the next crop of trees earlier. In essence, one needs to balance the rate of growth of mature trees against the higher rates of growth available by harvesting these trees and replacing them with younger, faster-growing ones. To demonstrate this, begin by considering bare land.

An initial investment in land for forestry purposes can be thought of as equating an initial investment in land $V(t)$ plus the cost of planting trees K to the present value of timber harvest plus subsequent release of bare land for further regeneration at t:

$$V(t) + K = [(p - c)v(t) + V(t)]e^{-rt}. \tag{1}$$

Upon setting $dV/dt = 0$ and rearranging terms, we derive the optimal financial (Faustmann) rotation age (van Kooten & Folmer 2004, pp. 365–371):

$$\frac{v'(t)}{v(t)} = \frac{r}{1 - e^{-rt}}. \tag{2}$$

The rotation age derived from Equation 2 depends only on commercial timber values and ignores environmental externalities including those associated with carbon fluxes.

5.2. Financial Rotation Age When Carbon Has Value

Carbon sequestered in managed forests could be sold as carbon offsets. Each year the landowner would receive carbon offset credits for the CO_2 removed from the atmosphere, which would depend on such factors as tree species, rates of growth, and biogeoclimatic zones. The offsets would be permanent and equivalent to an emissions reduction of the same amount. At the time of harvest, the landowner would need to purchase offsets based on the CO_2 released from the decay of logging residues and roadside wastes that are not removed, residues associated with processing and manufacturing, short- and long-lived products, and CO_2 released by fuel used in harvesting, transportation, and processing of logs. It is necessary to determine how much roundwood and other biomass is harvested and how this wood is utilized. Decay rates for each carbon pool can be established a priori, and the carbon fluxes resulting over infinite time can be discounted to the present to determine the emissions at harvest time (see Section 4.2).

The optimal rotation age is affected by environmental benefits that are realized continuously as opposed to only at the time of harvest. If environmental benefits depend on stand age, it is possible to find the optimal rotation age that considers both commercial timber and environmental values (Hartman 1976). Because carbon can be priced, it is possible to consider the impact on harvest age of a forest ecosystem's ability to sequester carbon. In determining the Hartman rotation age, environmental values are tied to the volume of commercial timber on the site, whereas carbon values are a function of the rate of change in volume—the rate of change in the forest ecosystem's biomass.

Growing trees sequester carbon at different rates, and harvesting releases carbon in the form of CO_2. The impact of penalizing carbon release is to delay harvest, whereas the prospect of replacing mature trees with younger, faster-growing trees leads to earlier harvests. Which of these two

outcomes dominates is determined by biophysical factors, what happens to stored carbon when trees are harvested, rates at which various carbon pools release carbon, and the urgency to address climate change.

Carbon uptake at any time is given by $\varphi v'(t)$, where φ is a parameter that translates cubic meters of biomass into carbon dioxide (t CO_2)—the offset credits created each year equal φ multiplied by the cubic meters of timber added to the growing stock. Further, let p^c be the price of carbon (\$/t CO_2) in the offset market (assumed here to be constant over time), β the fraction of timber that goes into long-term storage in structures and landfills (pickling factor), and r the discount rate. Offsets are purchased to cover any CO_2 released due to changes in the various ecosystem and product carbon pools due to harvest and decay of wood fiber over time. The amount of CO_2 released from burning fossil fuels during harvest, transportation, and processing is given by $\varphi(1–\beta)$ per cubic meter of timber harvested. In the model, the pickling parameter β takes into account future carbon fluxes in product pools and potentially emissions avoided when wood substitutes for nonwood in construction or for fossil fuel energy. In essence, the landowner is paid for tree growth that removes CO_2 from the atmosphere and penalized for CO_2 released at harvest, although there is no penalty for any carbon that subsequently enters a carbon pool where it might be stored for an indefinite period. Payments come from the sale of carbon offset credits, and a penalty comes as a requirement to purchase offsets.

The optimal rotation age that includes commercial timber benefits plus the externality benefits of CO_2 uptake and costs of emissions is determined by solving for t in the following (van Kooten et al. 1995, p. 369):

$$(p - c + \varphi\beta p^c)\frac{v'(t)}{v(t)} + r\varphi p^c = \frac{r}{1 - e^{-rt}}\left[p - c + \varphi\beta p^c + \frac{r\varphi p^c}{v(t)}\int_0^t v(s)e^{-rs}\,ds\right]. \tag{3}$$

If $p^c = 0$, we recover the expression in Equation 2 for determining the optimal financial rotation age.

We use the result in Equation 3 to investigate how various values of timber prices and costs, tree species and their growth, prices of carbon, and pickling factors could affect the optimal rotation age and thereby the potential supply and demand for carbon offset credits. The background information and parameter values for three different forest types are provided in **Table 1**. Parameter α gives the maximum volume on the stand (cubic meters per hectare), whereas δ and γ are shape parameters; the coastal rainforest is the fastest growing with the greatest volume of biomass at maturity, followed by the interior forest planted with genetically enhanced stock.

The scenarios in which the forest has both commercial value and value in mitigating climate change are provided in **Table 2** for discount rates of 2.5% and 5.0% and various values of the pickling factor (β) and carbon offset price (p^c). The results indicate times when the carbon benefits from leaving a forest unharvested may exceed the carbon plus commercial values from harvesting. This occurs for a small value of the pickling factor ($\beta \leq 0.5$) and a high price for carbon offsets ($p^c \geq \$50/\text{t } CO_2$). In essence, one would not harvest trees if the costs of releasing stored carbon by logging exceed the benefits of harvesting and selling logs plus the subsidies earned from replanting the site with young, fast-growing stems.

In most cases, the benefits of harvesting and selling logs plus the discounted earnings from sales of offset credits created when carbon is sequestered by regrowth exceed the value of the carbon offsets that would need to be purchased to cover the emissions released by commercial operations and decay of residues and postharvest wood fiber over time. As indicated in **Table 2**, this occurs for lower carbon prices and higher values of the pickling factor. Indeed, as β increases, more carbon is stored in long-lasting wood product pools so that when $\beta = 1$, no carbon is released by the current and future decay of postharvest fiber and logging and sawmilling residues. Indeed, if

Table 2 Optimal forest rotation ages (years) when carbon taxes and subsidies are taken into account: various forest types, carbon prices and pickling factors, and discount rates of 2.5% and 5.0%[a]

Pickling factor(β)	Financial rotation age	Price of carbon $25/t CO_2	$50/t CO_2	$100/t CO_2	$150/t CO_2	$200/t CO_2
		Coastal rainforest (years)				
	Discount rate 2.5%					
0		63	65	70	74	78
0.5	60	62	63	65	66	66
1		62	62	63	63	64
2		61	61	62	62	62
	Discount rate 5.0%					
0		70	NH[b]	NH	NH	NH
0.5	43	61	81	123	NH	NH
1		57	65	76	82	85
2		52	55	58	59	60
		Interior/boreal forest (years)				
	Discount rate 2.5%					
0		75	79	86	91	96
0.5	70	74	76	78	79	79
1		73	74	75	75	76
2		72	73	73	73	73
	Discount rate 5.0%					
0		105	175	NH	NH	NH
0.5	42	76	138	150	NH	NH
1		65	83	111	130	145
2		56	61	64	67	69
		Genetically enhanced interior/boreal forest (years)				
	Discount rate 2.5%					
0		39	42	46	50	52
0.5	37	39	40	41	41	42
1		38	39	39	40	40
2		38	38	38	38	39
	Discount rate 5.0%					
0		44	NH	NH	NH	NH
0.5	30	39	47	58	65	NH
1		35	40	44	45	47
2		35	36	37	37	37

Source: Authors' calculations.
[a]Beginning with tree planting.
[b]NH Indicates that the site remains unharvested.

$\beta > 1$, the landowner could receive carbon offsets over and above those created by storing carbon in products. This occurs when avoided fossil fuel emissions in the production of steel and/or concrete are credited to the harvesting of trees as wood products substitute for nonwood materials in construction.

The forgoing analysis does not explicitly consider the impact of biomass energy, although this could be addressed in a somewhat crude fashion by varying β. If bioenergy is carbon neutral, the

fossil fuel emissions would lead to the creation of carbon offsets and a higher value of β, which would cause the rotation age to decrease (**Table 2**). Using a forest rotation model that directly incorporates energy production profits and carbon sequestration benefits, McDermott et al. (2015) found that, contrary to our expectation, a manager who maximizes commercial timber values plus the income from burning biomass in lieu of fossil fuels will extend the optimal financial rotation age. The reason is that biomass burning was found not to be carbon neutral, thereby requiring the landowner to purchase offsets, which would reduce β and thereby the value of the timber on a site, lengthening the optimal rotation age.

Overall, the rotation age increases as the price of carbon increases and falls with the pickling factor. Unlike the financial rotation age, for which an increase in the discount rate reduced the rotation age, the impact of changes in the discount rate is ambiguous.

Although the foregoing analysis focuses on the forest rotation age when timber and carbon have value, forest ecosystems provide many types of nontimber amenities that range from water flow to forage for wild ungulates, and these vary in different and often noncontinuous ways with forest age (see Bowes & Krutilla 1989, Calish et al. 1978). Attempts to solve the returns to multiple amenity and commercial values lead to nonconvexities—the trade-offs among multiple conflicting values as a forest ages cannot be resolved (Swallow et al. 1990, Vincent & Binkley 1993). The problem of determining the optimal time to harvest a site is aggravated when forest management decisions on one site affect the amenity values on adjacent or spatially separated sites (Swallow & Wear 1993; Swallow et al. 1990, 1997). Optimal harvest decisions that consider amenity values across sites can be made under certain restrictive assumptions that are rarely found in the real world. One expects similar conclusions regarding the effect of carbon if leakages occurring at other sites are taken into account in determining the optimal rotation age or if the interplay between environmental, carbon, and commercial values is considered across time and space. Further research into these issues is required.

6. CONCLUDING DISCUSSION

This review evaluates the recent theory and evidence on the role of forest carbon offsets in mitigating atmospheric CO_2. The carbon offset credits that can be attributed to any forest project depend on the existing timber inventory (age, species, volume), current and future management regimes, sustainability constraints, timing of harvests, regeneration strategies, postharvest use of fiber, and the rate used to weight carbon fluxes depending on when they occur (Johnston & van Kooten 2015a). Offsets also depend on the baseline against which the path of carbon fluxes is to be compared. Many variables are political in nature, many are stochastic, and some are subject to lobbying. This makes it impossible to compare carbon offsets across forest projects, let alone compare to emissions offsets.

Our review finds that biomass burning in lieu of fossil fuels is a minor strategy that relies primarily on timber harvests for lumber production. In some cases, logging residues, roadside wastes, and sawmill residues become available at a very low cost; in other cases, it is too costly to transport residues and waste, or competition with other users makes such fiber too expensive to use as bioenergy. Even then, questions remain about the extent to which bioenergy is carbon neutral, which makes it difficult to determine if and how many offsets are created.

Further, this review teaches us that a forest model is needed to identify the carbon fluxes associated with different forest activities. For example, although outcomes are highly sensitive to baseline assumptions, model scenarios are highly uncertain and unlikely to be realized due to the difficulty of contracting. The creation of forest carbon offsets is also sensitive to the time frame employed and the rate used to weight carbon fluxes as to when they occur. Finally, results are

sensitive to assumptions regarding which carbon sinks to include and whether avoided emissions (e.g., from burning fossil fuels to generate electricity or produce concrete or steel) are included in calculating carbon fluxes. We also learn that leaving forests in an unmanaged state is often the least effective approach for mitigating climate change. When bundled with other environmental services, a case could be made for conservation, but it would be difficult to measure the carbon offsets that might legitimately be produced.

Clearly, more research is needed to better understand how forest carbon offsets translate into actual emission reductions. The literature provides a wide range of estimates on this matter and appears to be sensitive to the technique employed in evaluation (van Kooten & Sohngen 2007; van Kooten et al. 2004, 2009). The creation of carbon offsets would also benefit from a more transparent link between forestland owners and the purchaser of offsets. Absent from the literature are rigorous analyses comparing theoretically derived measures of carbon offsets to actual emissions savings over time. Admittedly, many policies pertaining to forest carbon flux are still being worked out and data on their effectiveness are not yet available. Overall, we find that greater care might be needed in the identification of forest-sector carbon offsets if these are to be traded in emissions markets.

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